Nano-materials & Silicon Nanotechnology

C. Michael Garner

Intel Corporation

Agenda

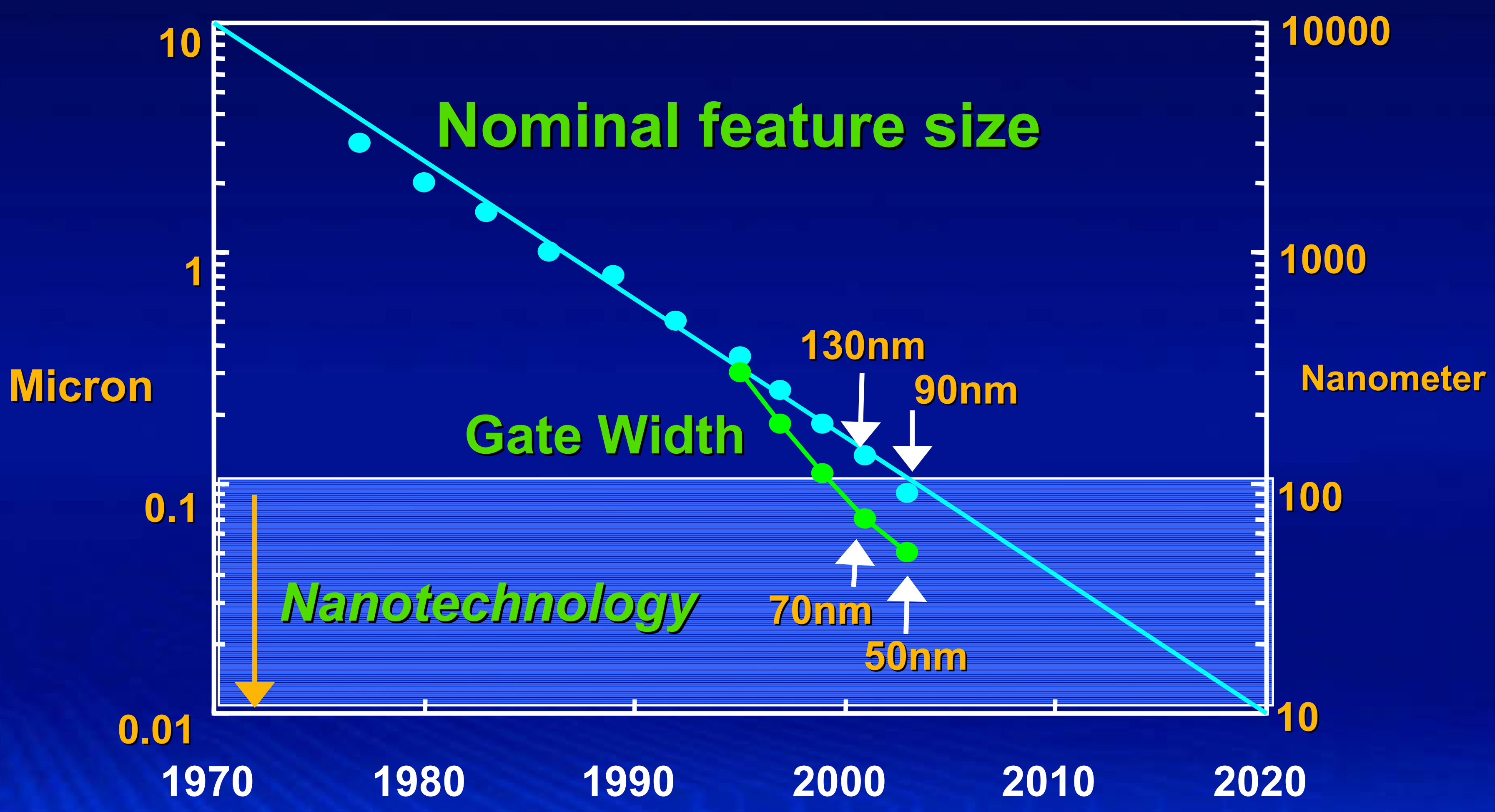
- Technology Scaling and Moore's Law
- Technology Challenges
- Nanotechnology Building Blocks
- Nano-material Opportunities
- Beyond the roadmap….
- Summary

Key Messages

- Silicon Nanotechnology is production reality and follows Moore's law
- Experimental data on 22nm-node/10nm-minimum-feature-size
- We believe that silicon nanotechnology is extendable to 2015
- Open minded about post-2015 options
- Nano-materials will play an important role in the silicon nanotechnology platform

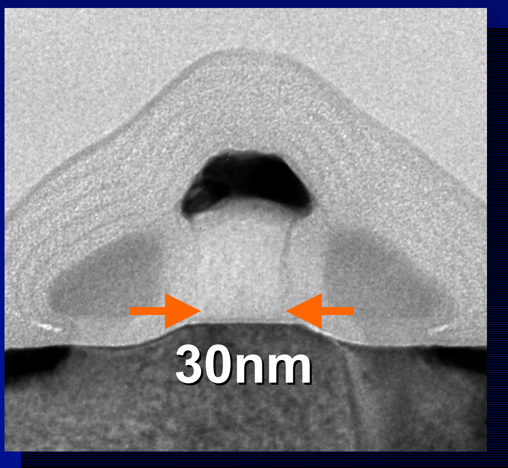
Nanotechnology could deliver critical materials

Technology Scaling

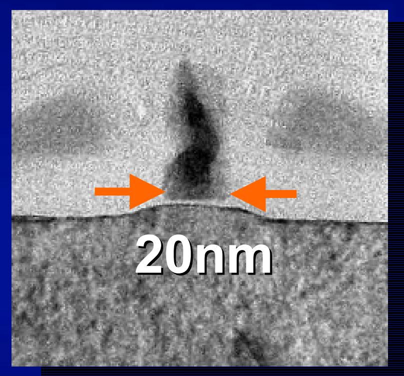


Intel's Transistor Research in Deep Nanotechnology Space

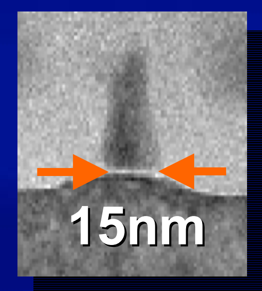
Experimental transistors for future process generations



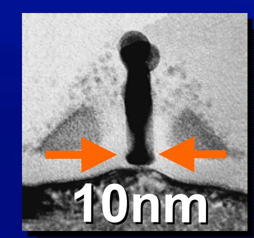
65nm process
2005 production



45nm process
2007 production



32nm process
2009 production

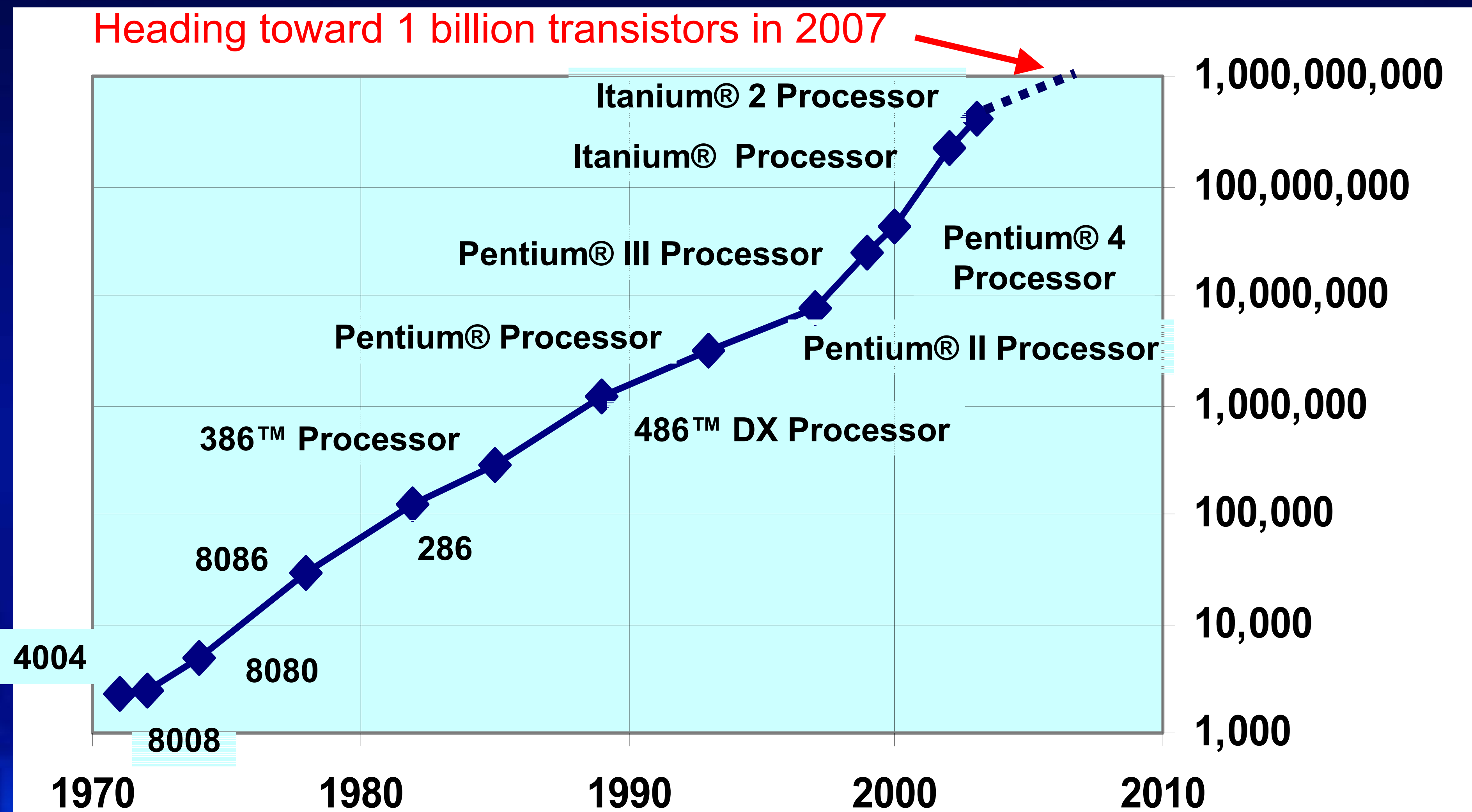


22nm process
2011 production

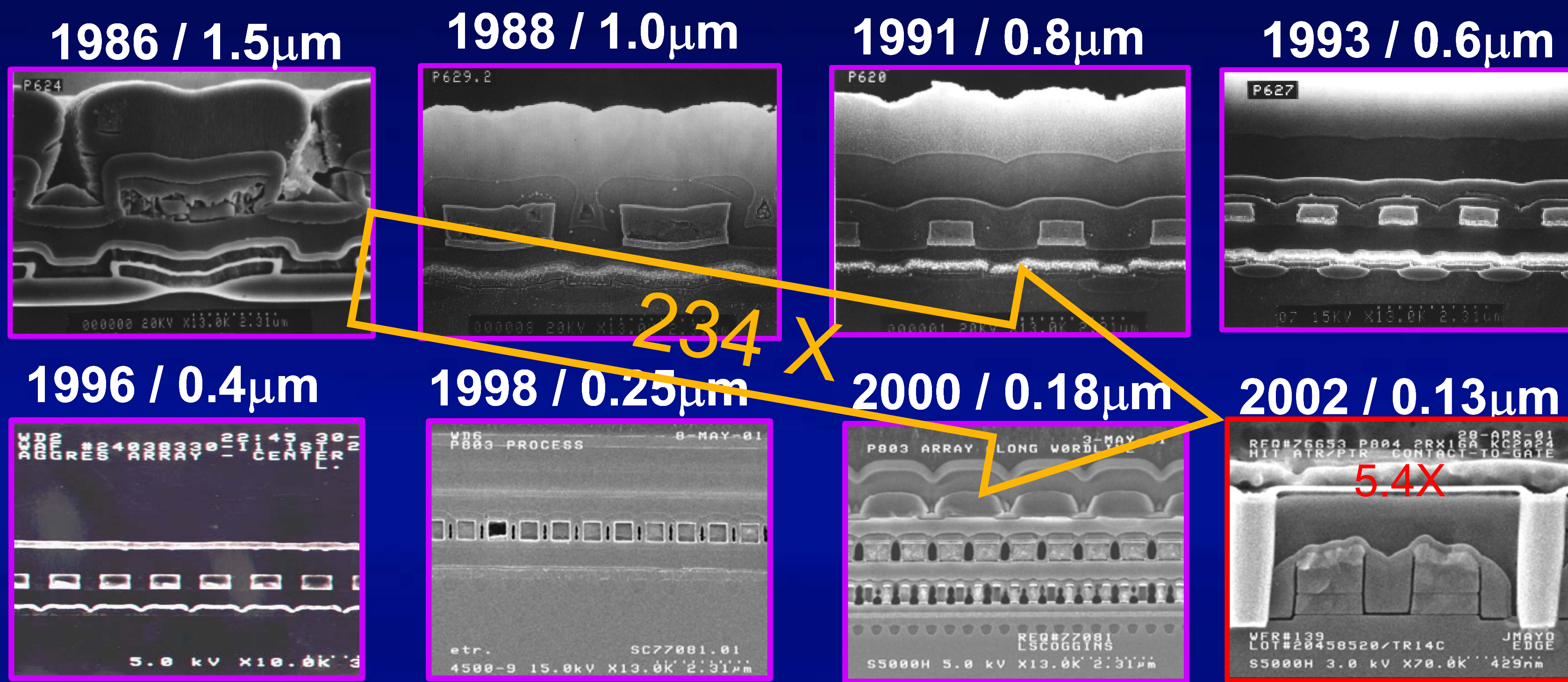
Transistors will be improved for production

Source: Intel

Moore's Law Continues



Flash (ETOX®) Technology Scaling



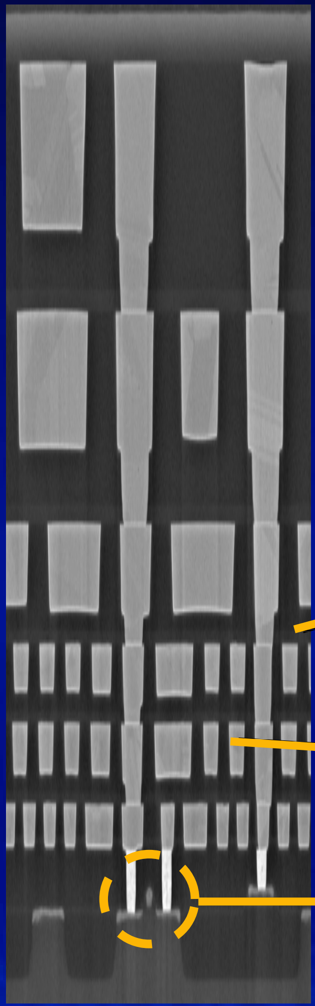
Volume Production Year / Technology Generation

18 years and 8 Generations of ETOX® to 0.13 µm

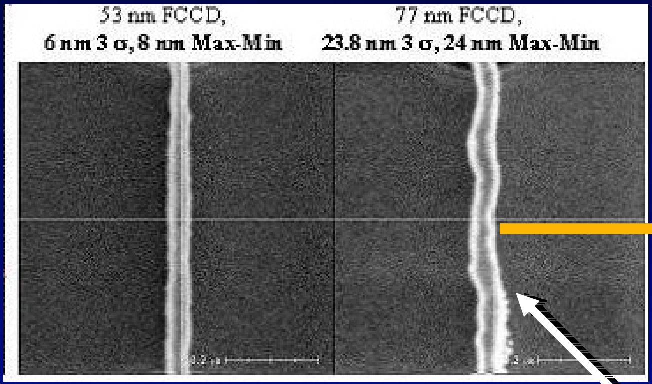
Silicon Scaling Leads to Material Challenges

- Lithography
- Transistors
- Interconnects
- Package

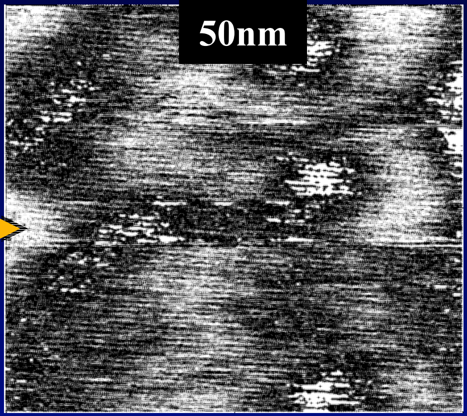
Material Challenges



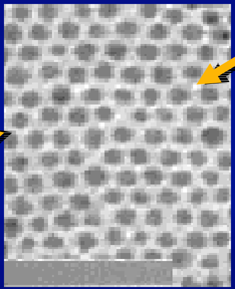
PPT Shrink
Source: Intel



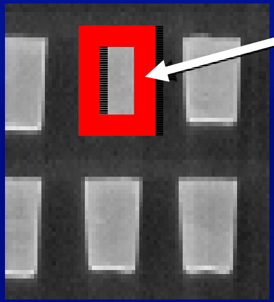
Print Features Line Edge Roughness(LER)



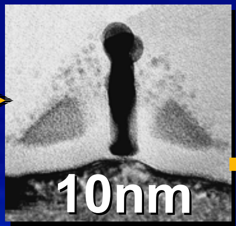
Resist Nano-domains



Low K Interlevel Dielectric
Micelle Assembled.....



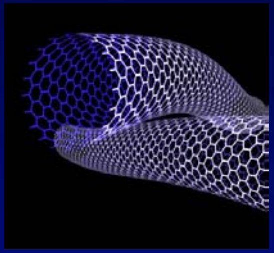
Barrier Layer ~20nm



What Device Next?
What Materials?
How to Assemble?

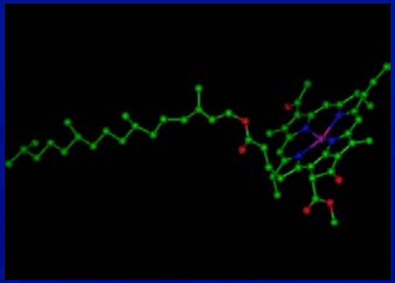
Materials Challenges Everywhere

Nanotech Building Blocks

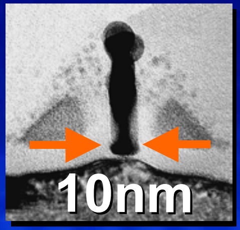


Sub 100nm particles

Molecular Assembly (directed and self assembly)

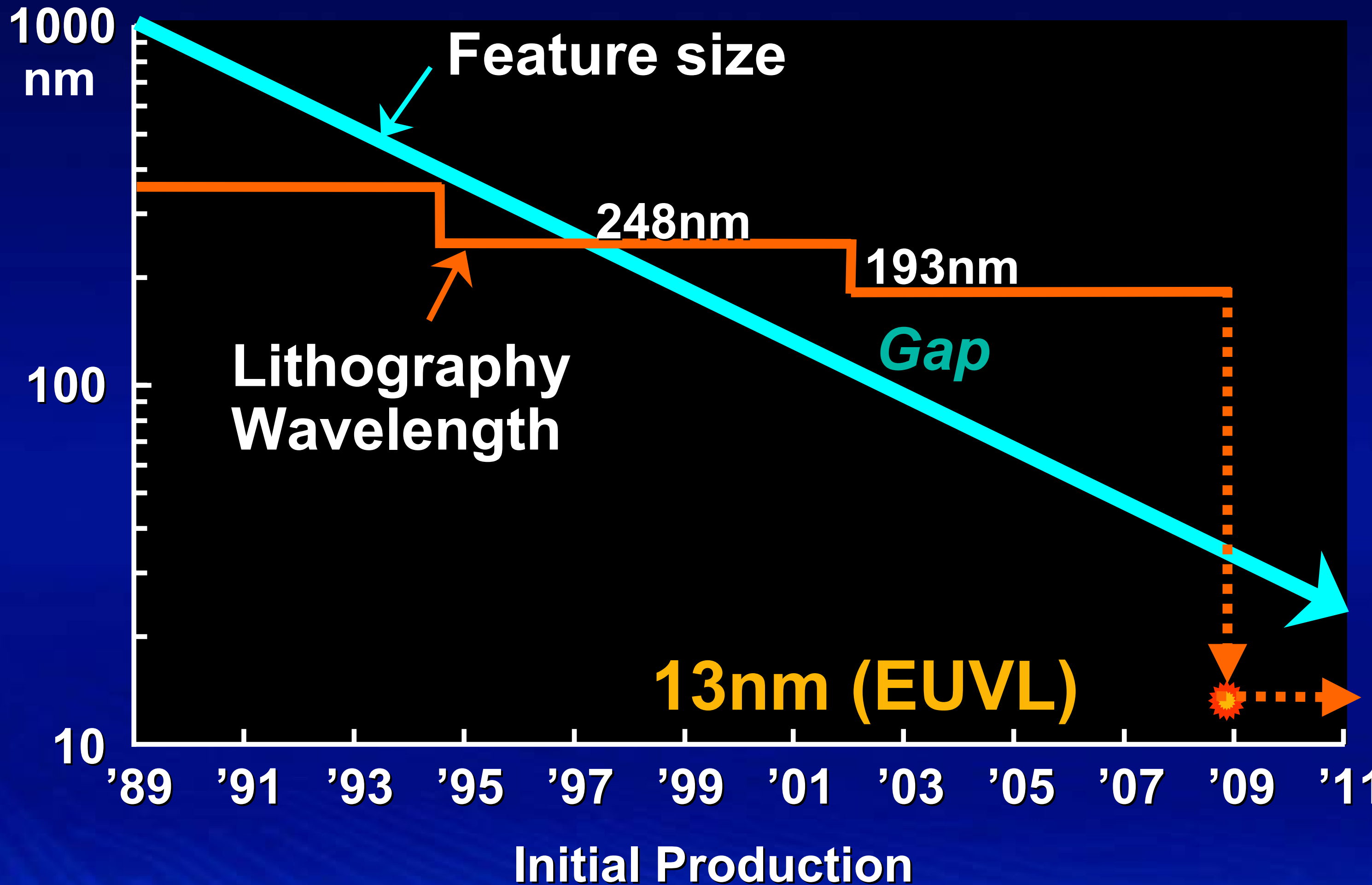


Macromolecules



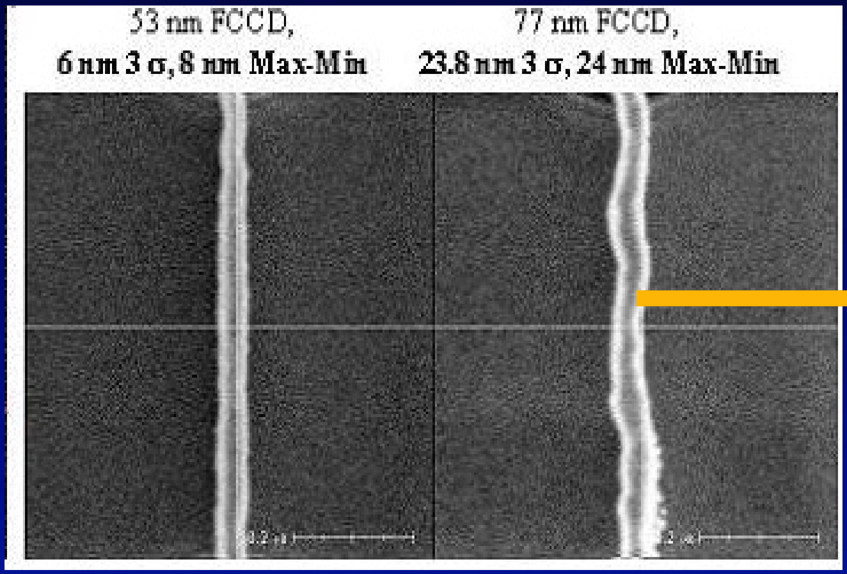
Sub 100nm structures

Lithography Challenges

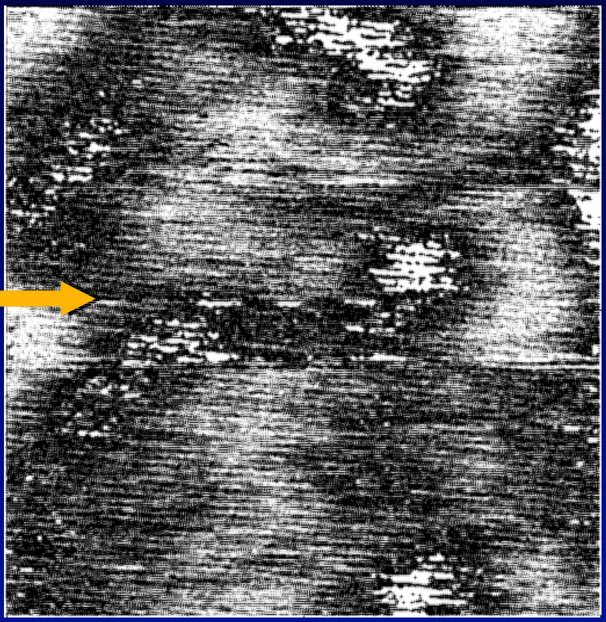


New Mask, Design Techniques, and Materials Needed to Support future Lithography Scaling

Future Lithography Resist Challenges



Line Edge Roughness(LER)



Atomic Force Microscope Picture of Resist Nano-domains

- Resist nano-domains limiting feature resolution and defects.
  - *Requires control at the molecular level*

New Materials, Devices Extend Si Scaling

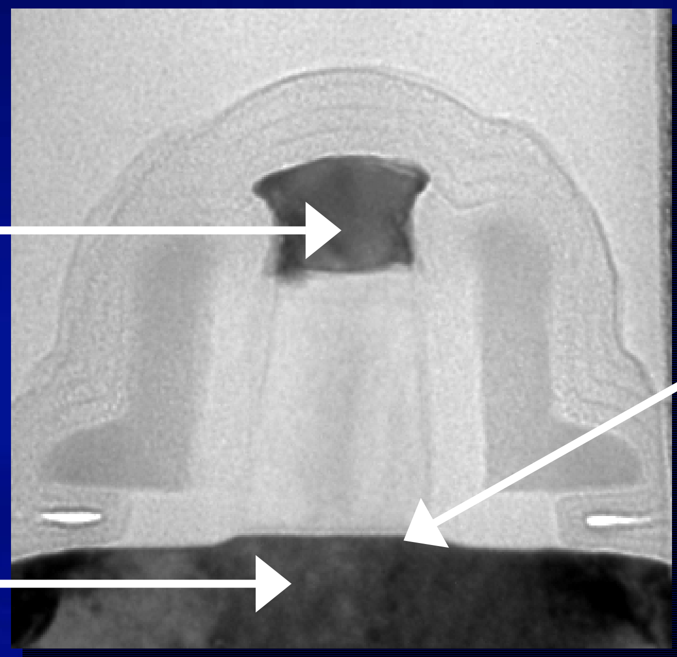
Changes Made

Gate

Silicide added

Channel

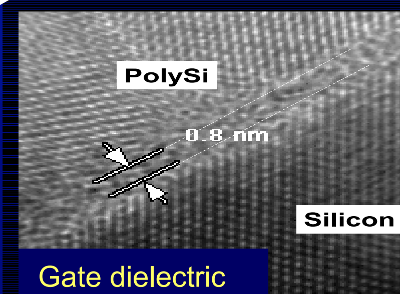
Strained silicon



Transistor

Future Options

High-k gate dielectric



Gate dielectric less than 3 atomic layers thick

Source: Intel

Source: Intel

New Materials, Devices Extend Si Scaling

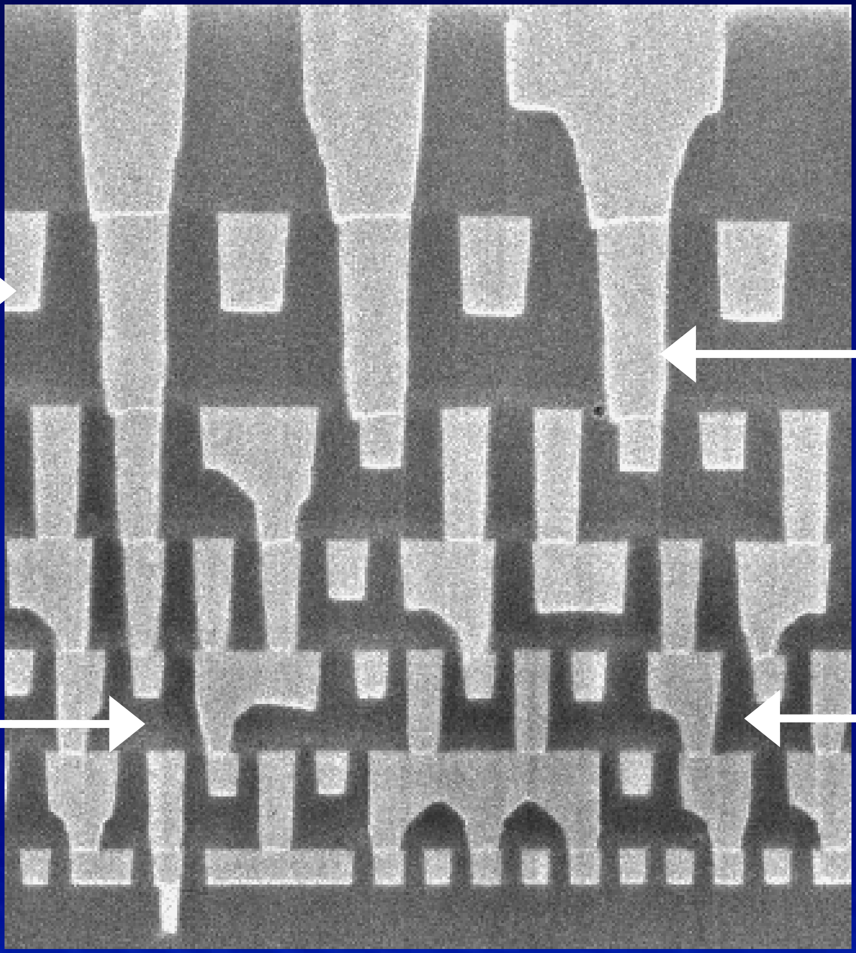
Changes Made

Metal lines

Al → Cu

Insulating dielectric

SiO_2 → SiOF → CDO (low-k)



Interconnects

Source: Intel

Future Options

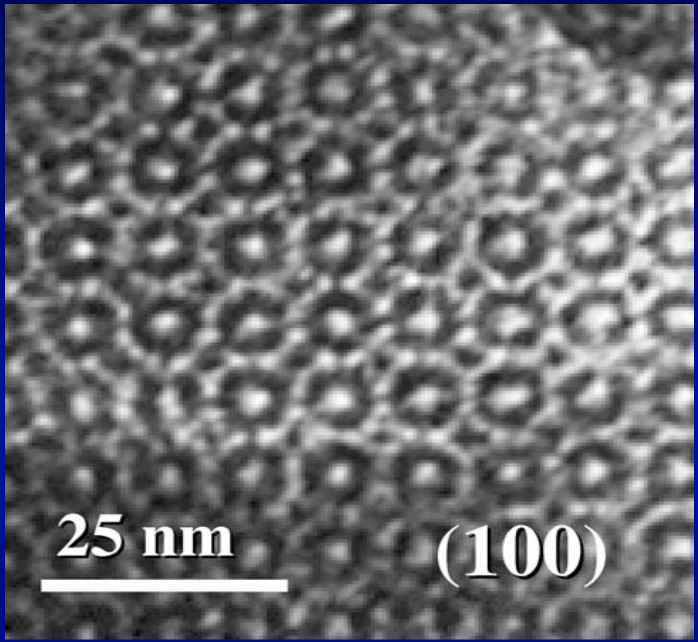
New Thinner Barrier Layers

Ultra Low-k Dielectric

intel®

Molecular Self-Assembly

Low-K Dielectric



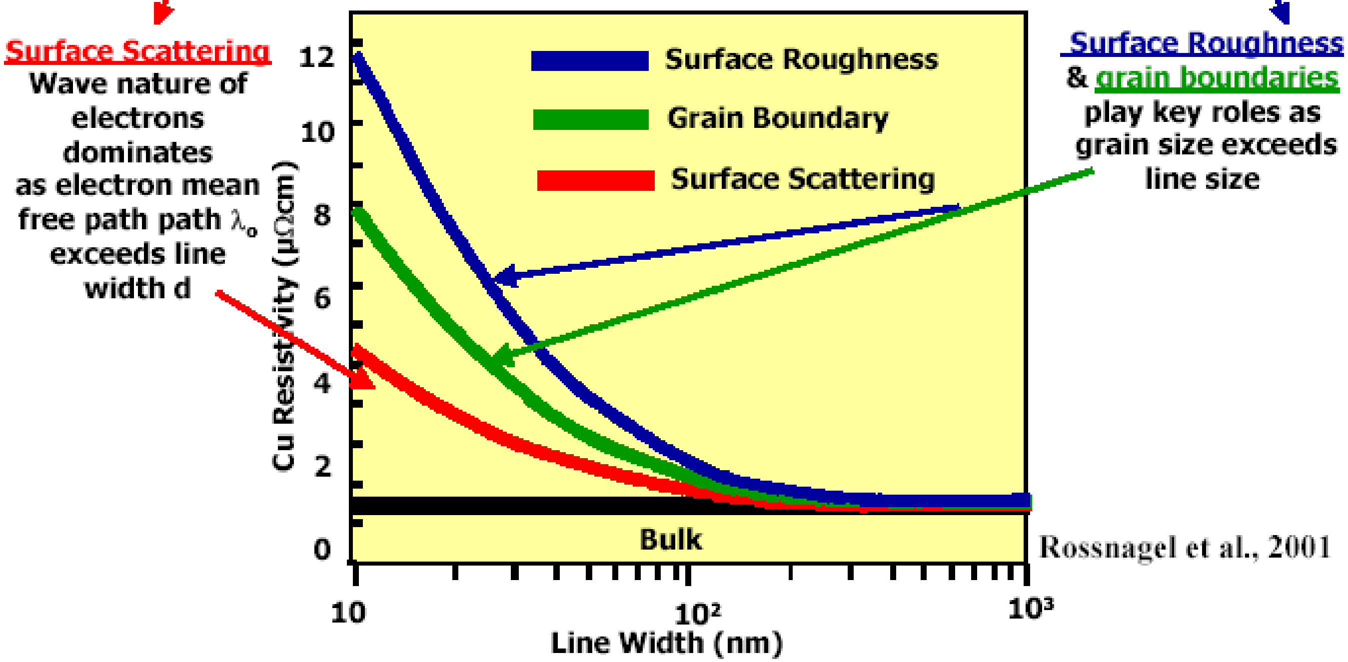
Source: J. Brinker, UNM/Sandia National Labs

- **Materials of the gel self-organize into a Low K dielectric**
- **Assembly driven by two-sided organic surfactant molecules**

Conductivity Challenge

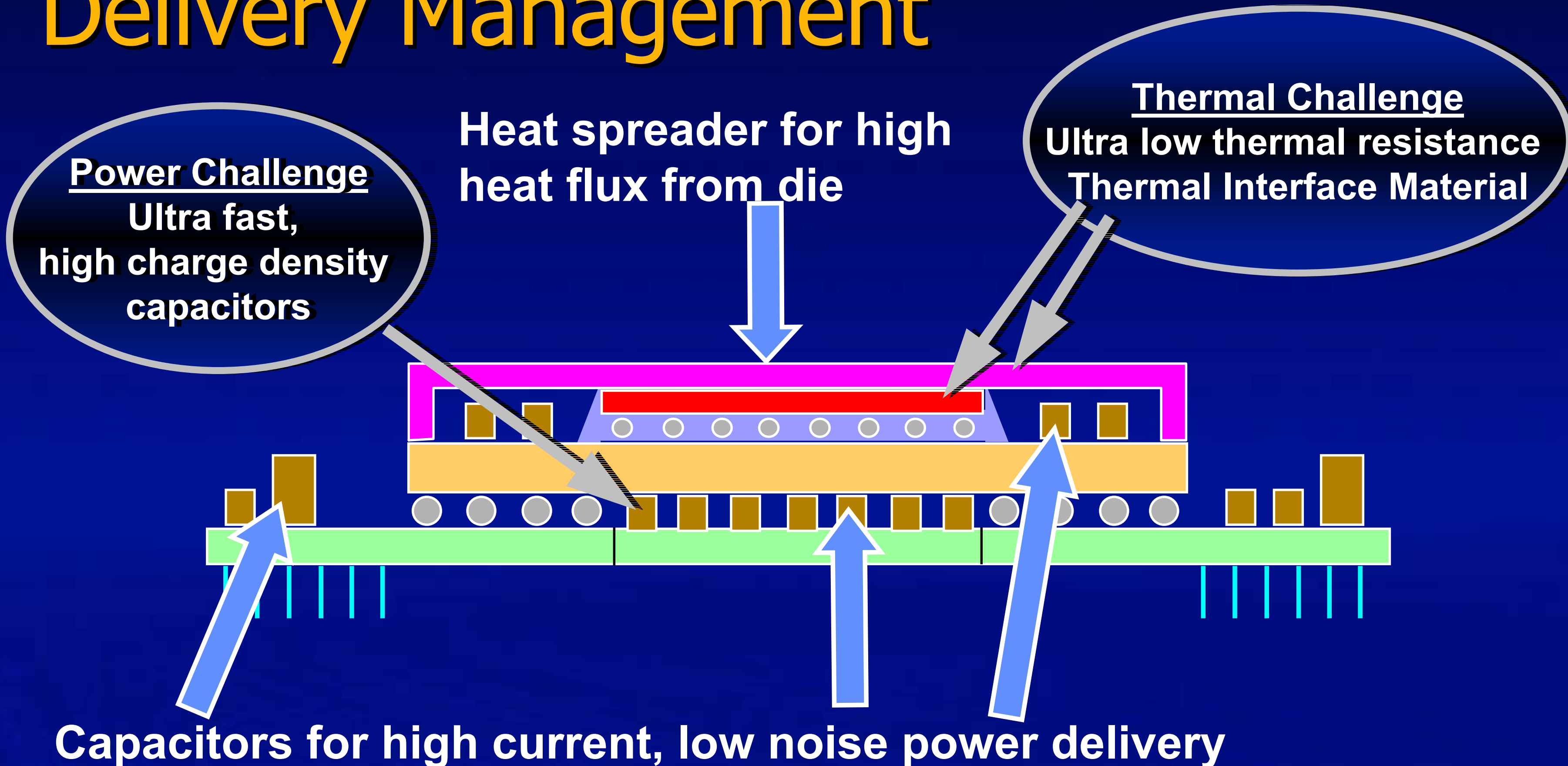
Morphological vs. Fundamental (Physics) Limits to Conductivity

Electrical resistivity in sub-50 nm conductor lines rises prohibitively due to quantum mechanical phenomena and microstructural limitations



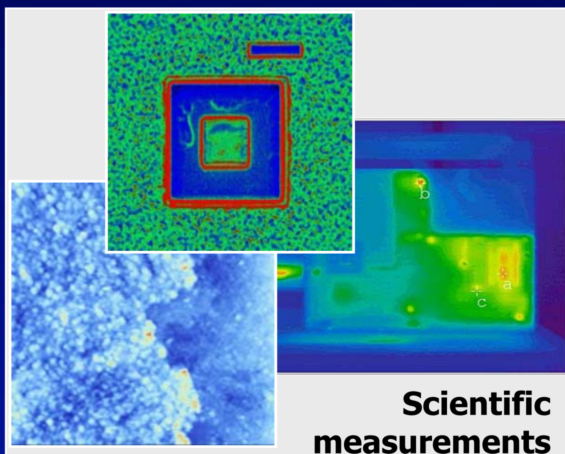
Nanomaterials to reduce roughness & grain scattering

Integrated Thermal and Power Delivery Management



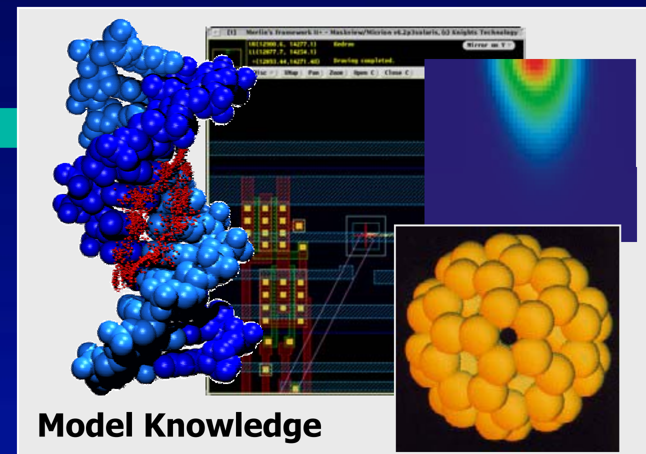
Nano-material Opportunities in Thermal and Power Delivery

Characterization Techniques



Physics-based Computer Vision

Quantitative Understanding



- **Interpret images in conjunction with physical models**
  - → **Focus on nanoscale sources such as AFMs, STMs, FIB**
- **New metrology is needed……**
  - → **Faster structural analysis**
  - → **Nano-composition analysis**
  - → **Monitor chemical reactions**

Beyond the roadmap....

- Many device options....
- Compatibility with CMOS for evolutionary introduction
- Directed or self assembly of arrays???
  - ➔Defect density or purity required....
- Self correcting architectures??
- Nanotechnology needs a richer suite of functionality…

Collaboration between Industry, Universities, and Government is essential

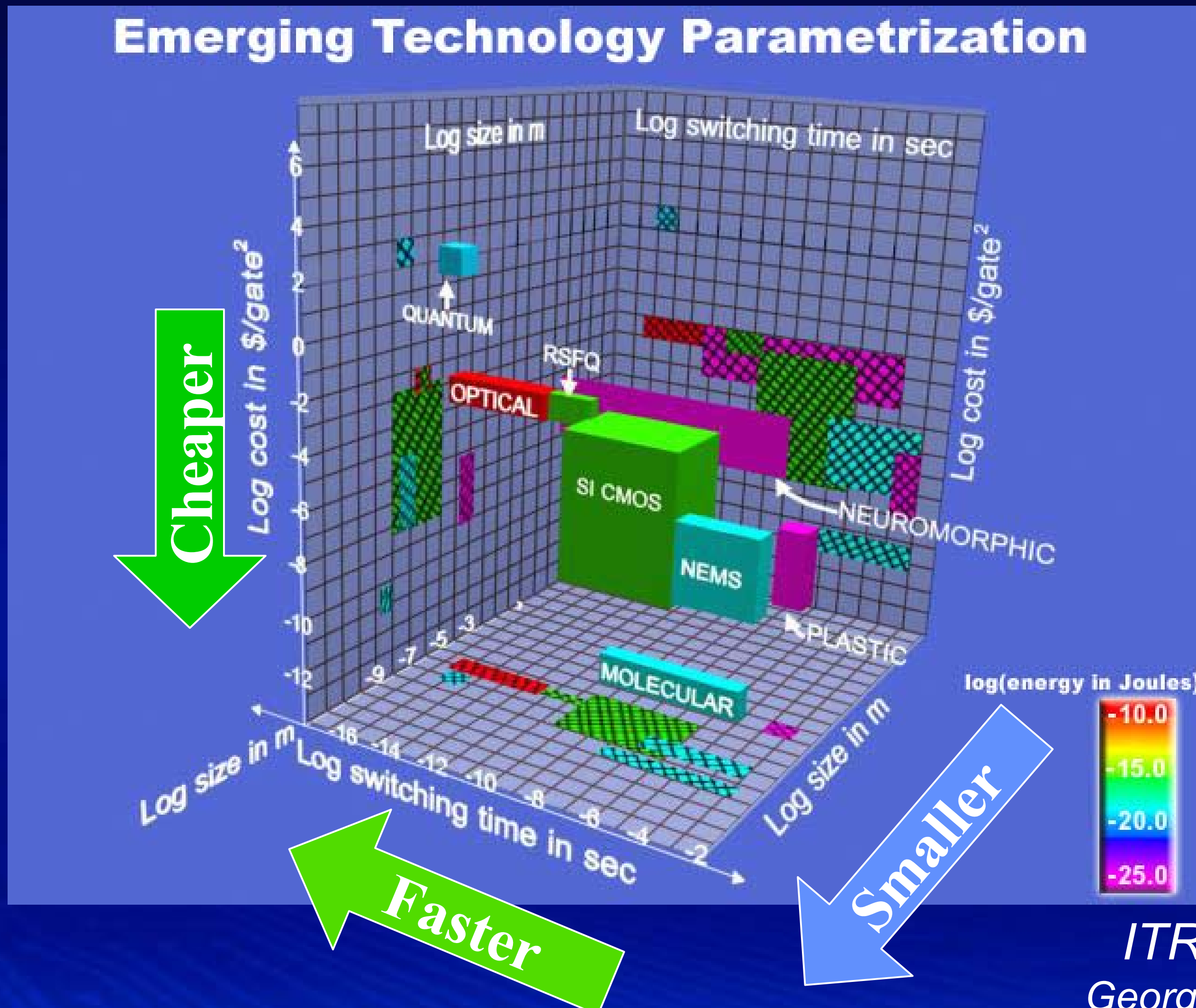
What are we looking for?

- Required characteristics:
  - → Scalability
  - → Performance
  - → Energy efficiency
  - → Gain
  - → Operational reliability
  - → Room temp. operation
- Preferred approach:
  - → CMOS process compatibility
  - → CMOS architectural compatibility

Alternative state variables

- **Spin–electron, nuclear, photon**
- **Phase**
- **Quantum state**
- **Magnetic flux quanta**
- **Mechanical deformation**
- **Dipole orientation**
- **Molecular state**

Some Alternative Logic Devices

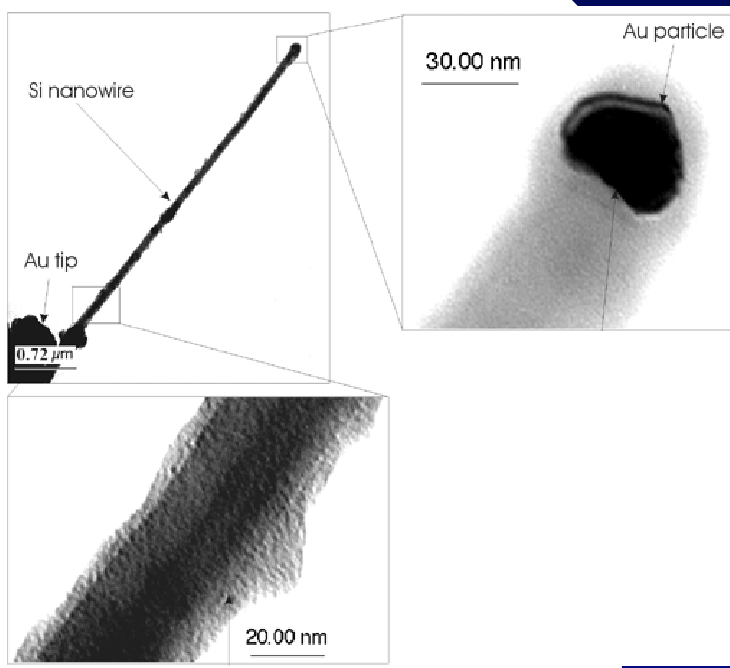


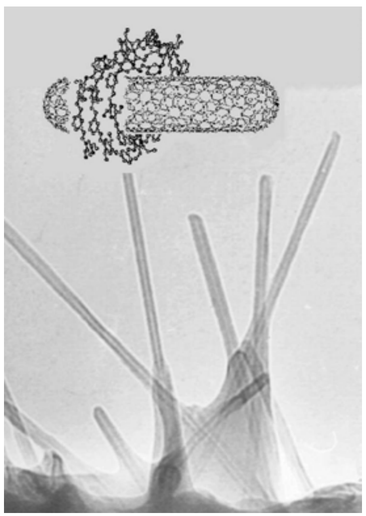
ITRS, 2000
George Bourianoff

Alternative logic devices exist and are complimentary to scaled silicon

Future Nanotechnology will compliment & extend Silicon Technology

Silicon Nanowire*





Carbon Nanotube**

Nanotube/Nanowire Transistors

*Source: Holmes et al, University College Cork
**Source: Blau et al, Trinity College Dublin

Many options, but no clear winners…

Summary

- Many new materials required for scaling
  - ➔Lithography
  - ➔Transistor
  - ➔Interconnects
  - ➔Non-volatile Memory
  - ➔Thermal & Power Delivery Materials
- Silicon is the platform for the future
- Nanotechnology could deliver critical materials to support Silicon Nanotechnology
- For technology beyond 2015 collaboration between Industry, Universities, and Government is essential

Back-up

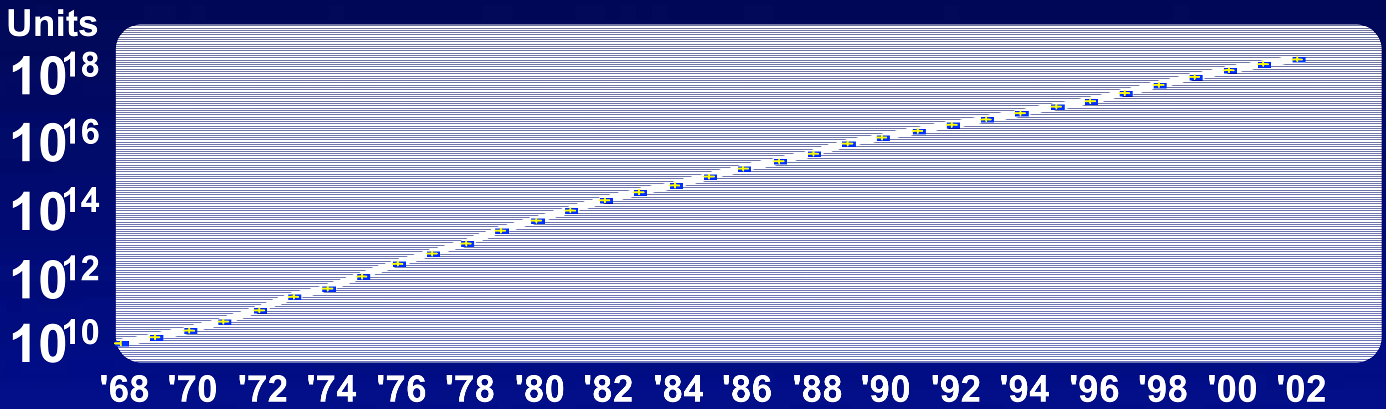
Quest for New Materials

Year	1997	1999	2001	2003	2005	2007	2009	2011
	P856	P858	PX60	P1262	P1264	P1266	P1268	P1270
Node	0.25µm	0.18 µm	130nm	90nm	65nm	45nm	32nm	22nm
Metal	Al	→	Cu	→	→	→	→	?
ILD	SiO2	SiOF	→	SiOC	→	→	?	?
Gate Ox	SiO2	→	→	→	High-k	?	?	?
Gate Electrode	Poly	→	→	→	→	Metal	?	?

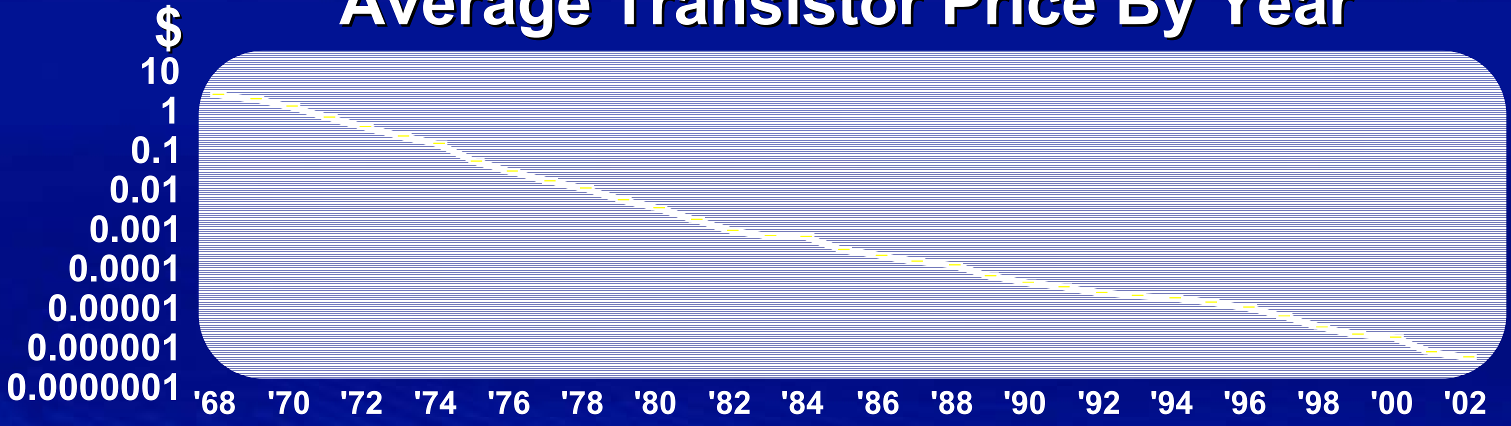
Extending Moore's Law with Novel Materials

Moore's Law in Action...

Transistors Shipped Per Year



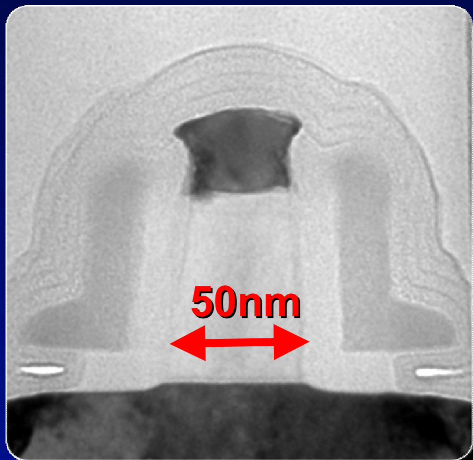
Average Transistor Price By Year



Source: Dataquest/Intel, 12/02

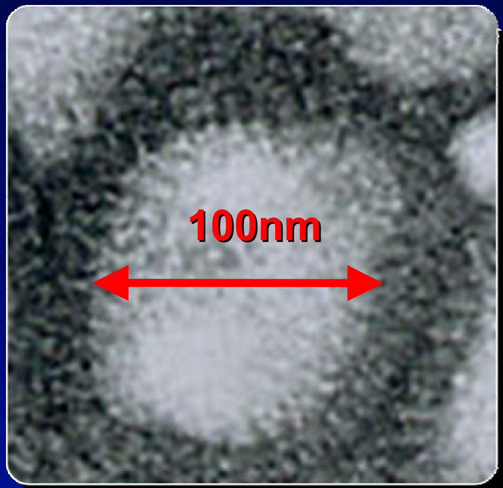
Moore's Law is driven by economics

Precision Biology



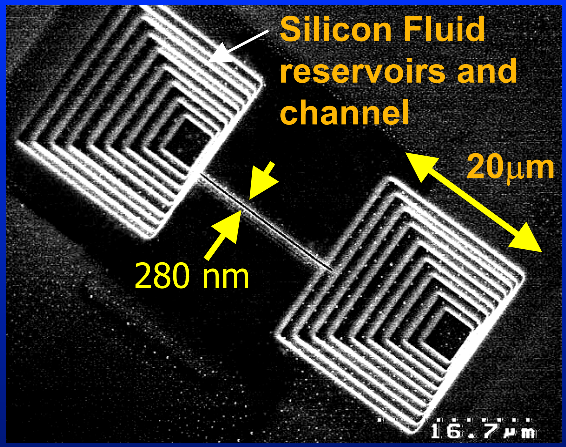
Transistor for 90nm Process

Source: Intel



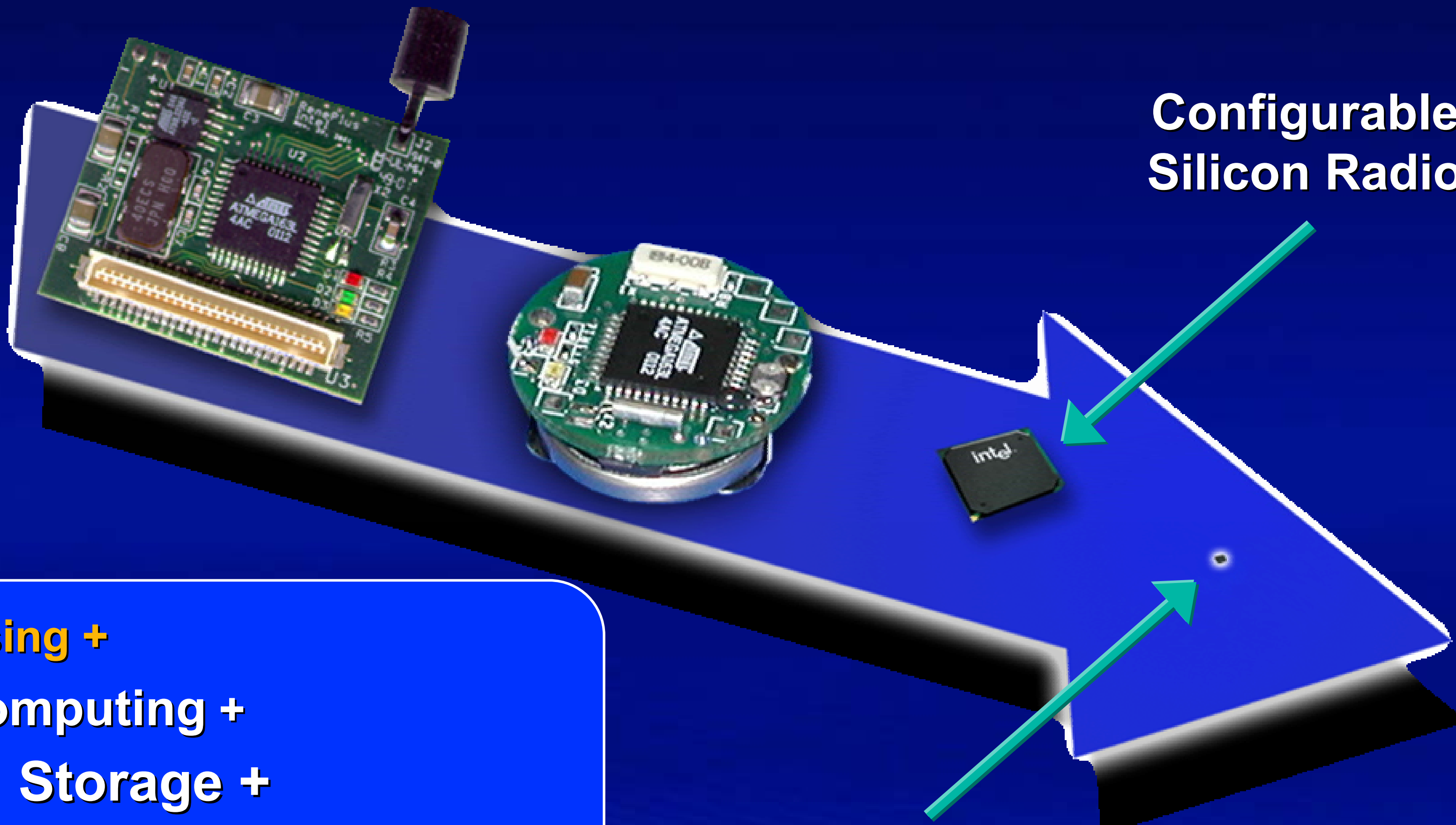
Influenza virus

Source: CDC



Create a new generation of bio-instruments capable of operating in the *single-molecule* regime

The road to smart dust….



Sensing +

Computing +

Storage +

Communicating

Nanotechnology Opportunities

Extending Moore's Law

- Synergistic extension of Silicon Technology
  - → Si-based CMOS transistors through 2015
  - → Role for new materials based on nanotechnology
  - → Open minded about options beyond 2015

Expanding Moore's Law

- Proactive Computing Vision

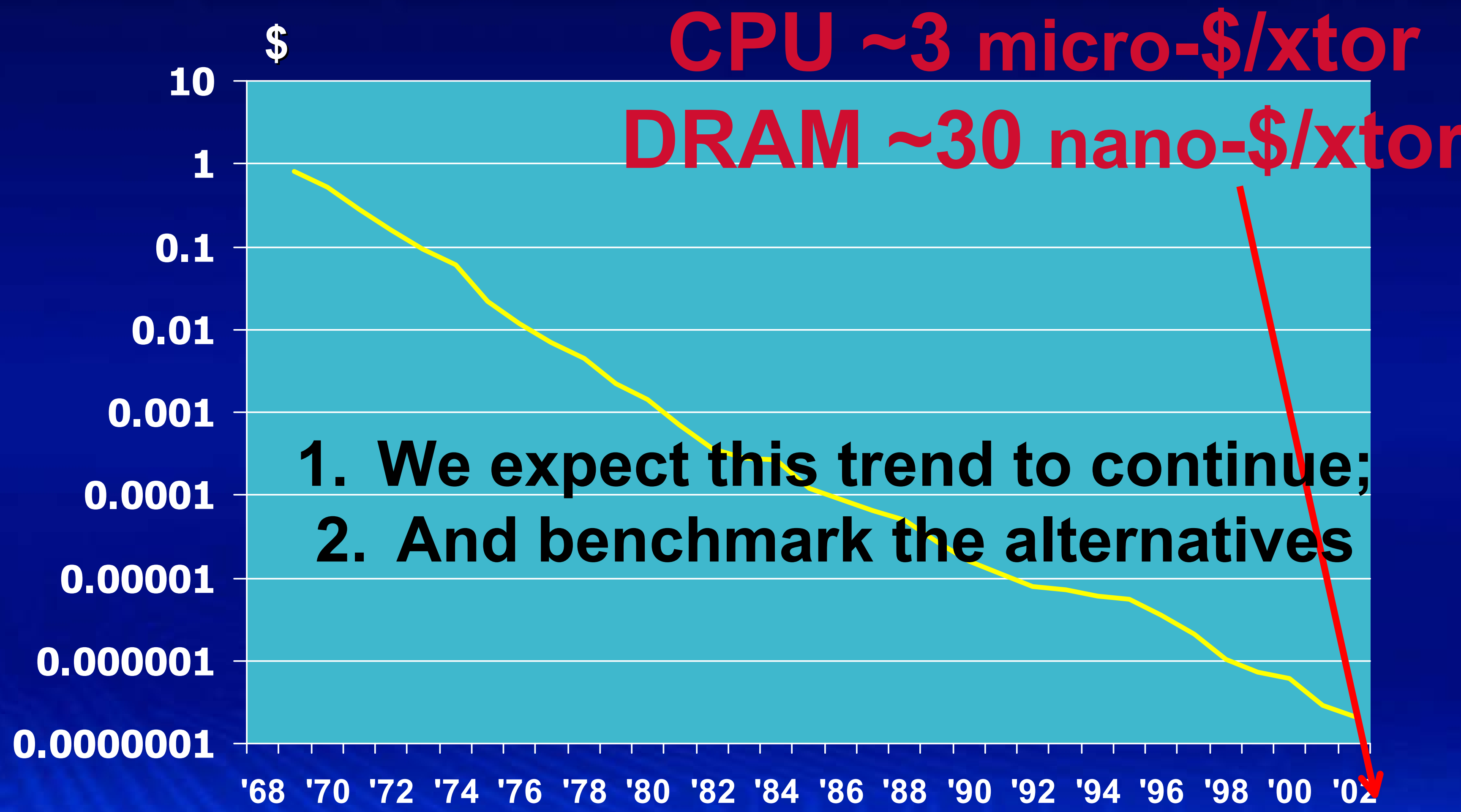
Collaboration between Industries, Universities, and Governments is essential

What is Nanotechnology?

a. New structures like carbon nanotubes
b. Silicon devices made smaller
c. Arranging atoms and molecules
d. Letting atoms assemble themselves
e. Something far in the future
f. In production today
g. All of the above

Correct answer: g.

$ per transistor decreased by > 6 orders in 30 years: This drives investments



Source: WSTS/Dataquest/Intel, 8/02

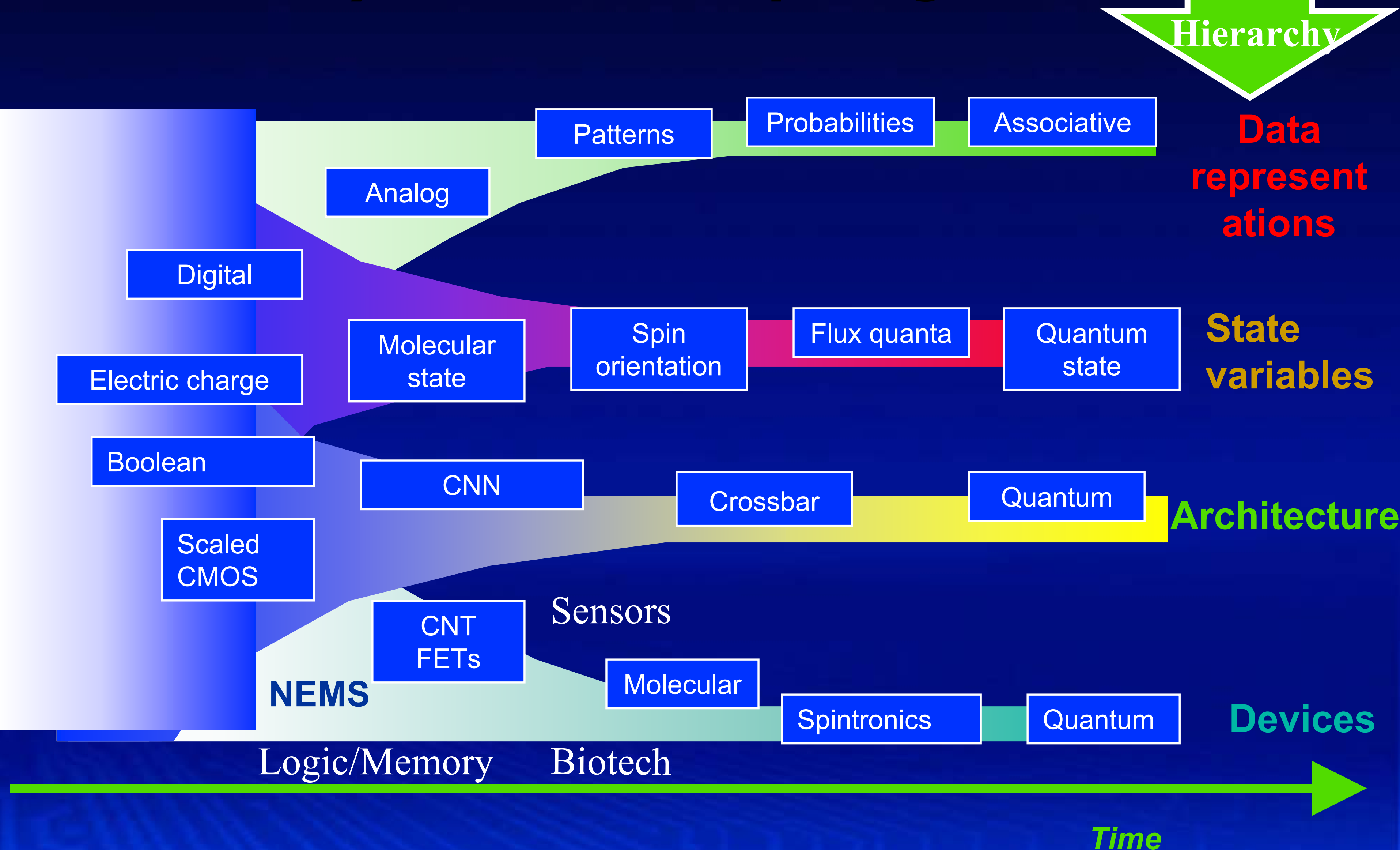
What are the Alternative Devices?

Logic Device	Perf.	Arch. compat	Reliability	Proc. compat	Op. temp	Energ eff	Sensitivity	Scalability
Flux	3	2	3	2	1	1	2	1
1D	2	3	1	2	3	3	3	3
Resonant Tunneling	2	2	2	2	2	3	1	2
SETs	1	1	1	2	1	2	1	2
Molecular	1	1	3	2	2	2	3	3
QCA	1	1	2	1	1	2	3	2
Spin	2	2	1	2	1	2	1	3
Quantum	3	2	1	1	1	3	1	3

(From ITRS ERD TWIG 2003)

Molecular, spin, quantum stand out

A Taxonomy for Nano-computing



Courtesy: George Bourianoff